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Image digitization of discontinuous and degraded electrocardiogram paper records using an entropy-based bit plane slicing algorithm

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ABSTRACT

Background: Electrocardiograms (ECGs) are routinely recorded and stored in a variety of paper or scanned image format. Current ECG recording machines record ECG on graph paper, also it provides digitized ECG signal along with automated cardiovascular diagnosis (CVD). However, such recording machines cannot analyse preserved paper ECG records as it requires input in terms of digitized signal. Therefore, it is important to extract ECG signal from these preserved paper ECG records using digitization method. There are different paper degradations that adversely affect digitization process. The purpose of this work is to perform an image enhancement and digitization of the degraded ECG images to extract continuous ECG signal.
Methods: In this paper, we propose entropy-based bit plane slicing (EBPS) algorithm in which pre-processing is done using dominant color detection and local bit plane slicing. Maximum entropy based adaptive bit plane selection is applied to the pre-processed image. Discontinuous ECG correction (DECGC) is then done to produce continuous ECG signal.
Results: The algorithm is tested on 836 different degraded paper ECG records obtained from various diagnostic centers. After analysis with 101 known ground truth ECG signals the accuracy, sensitivity, specificity and overall F-measure of ECG is 99.42%, 99.69%, 99.81% and 99.26% respectively. The RMS error and correlation between the extracted digitized signal and ground truth for 101 cases is 0.040 and 99.89% respectively.
Conclusions: The EBPS method is able to remove all types of degradation in paper ECG records to generate a uniform digitized signal. Instead of manual measurement and prediction from archived paper ECG records, automated prediction (using already existing cardiovascular diagnosis software) is possible with the help of extracted digitized signal obtained using proposed digitization method, which will also help retrospective cardiovascular analysis.

Introduction

Electrocardiogram (ECG) is commonly recorded for analysis of cardiac problems. In developing countries [1], roughly about 90% hospitals or clinical departments routinely record ECG on a variety of graph papers and these records are preserved by either patient or clinical department. Such preserved ECG records are degraded [2] with various types of noise like signal discontinuity due to ink evaporation, blurring and folding of paper ECG record. This paper majorly focuses on preserved or older resting ECGs. Nowadays printed ECG graph paper is scanned and stored as an image. The problems with storage in the form of the scanned image are, it requires large storage space, transmission requires more bandwidth and time, the addition of noise during scanning (such as marginal noise) [3,4]. Though previous research focused on digitization of scanned image of the printed signal [5,6], nowadays image can be immediately obtained with a cell phone [7]. However such cell phone images also have problems like no uniform illumination, low contrast due to lack of sufficient or controllable lightning, and lack of adjustable camera exposure time and aperture size. All these problems make the scanned image as well as cell phone captured image difficult for diagnosis. The focus of this work is on handling various degradations occurring in older resting ECGs and extraction of clear and continuous ECG signal trace for better analysis and interpretation.

Latest ECG recording machines stores ECG recording in terms of digitized ECG signal along with automated cardiovascular diagnosis (CVD) [8,9]. However, such recording machines, which has automated diagnosis software cannot analyse preserved paper ECG records as it requires input in terms of one-dimensional time series digital signal (vector) and not as paper ECG record or as scanned ECG image. Hence to develop an application for digitization and image enhancement (noise removal) of preserved (degraded) paper ECG records and extracting signal from unstructured ECG graph paper records [10,11] is the immediate need. These digitized signals may be useful for retrospective cardiovascular analysis [12]. In the long run, it is important to conserve the documented ECG graph paper records in a uniform format and in single

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database [1] for quick retrieval in data mining to maximizing research in the area of cardiac electrophysiology.

Methods

In the proposed entropy-based bit plane slicing (EBPS) algorithm, first degraded ECG graph paper records are scanned at 200 dpi (dots per inch) [13,14]and stored in png format. The size of the image is then measured in terms of spatial resolution (pixels) in MATLAB and each side of the image is cropped down in order to remove any border present in an ECG signal (cropping size of 40 pixels from each side).

Dominant color extraction [15] is carried out by separating color planes and considering each R, G and B plane separately as a grey scale image. The average values from each of these grey scale images are extracted after neglecting pixels in vicinity ±5 pixels). Sample average value of red color plane is computed using formula shown below:

$$AVG_R = \sum_{m=i} \sum_{n=j} I(m,n)/(i * j) \tag{1}$$

$\forall \mathrm{I}_{m,n} \notin AVG_R \pm 5$ pixel

where,

AVG_R = average grey value of red color plane
i = all number of rows
j = all number of columns
I (m,n) = each pixel value at m*th* and n*th* instance of the loop

Similarly, sample averages are calculated for B and G color planes as well. The dominant color is determined using these three R G B values and the adaptive threshold is then applied. The threshold is set as per the average grey value of the image as shown by Fig. 6B. After dominant color determination, grey plane, red plane, green plane and blue plane (RGB planes) are separated from the image. The selected grey plane image is then contrast stretched to the limits from 0 to 255. After contrast stretching all the 8 different bit planes are extracted [16] from the selected plane image as shown in Supplementary Fig. S2. Mostly the required information (i.e. ECG signal trace) is available in 7*th* and 8*th* bit plane, as shown in Fig. 1. Out of eight extracted planes, correct plane (which has only ECG signal trace) is selected using maximum entropy method which separates ECG signal trace from background grid as per the following formula,

$$I_m(x,y) = I_N(x,y), \forall I_N(x,y) \in R \tag{2}$$

where,

R- range of values lying between 2^{m-1} and 2^m
m- current bit plane under computation
x- range from 1 to m
y- range from 1 to n and (m, n) is size of image and (x, y) is current pixel under computation and if $I_m(x, y)$ exists then

$$I_{N-1}(x,y) = I_N(x,y) - 2^{\mathrm{m}-1} \tag{3}$$

where,

m = bit plane
I_N = input image for *mth* bit plane extraction

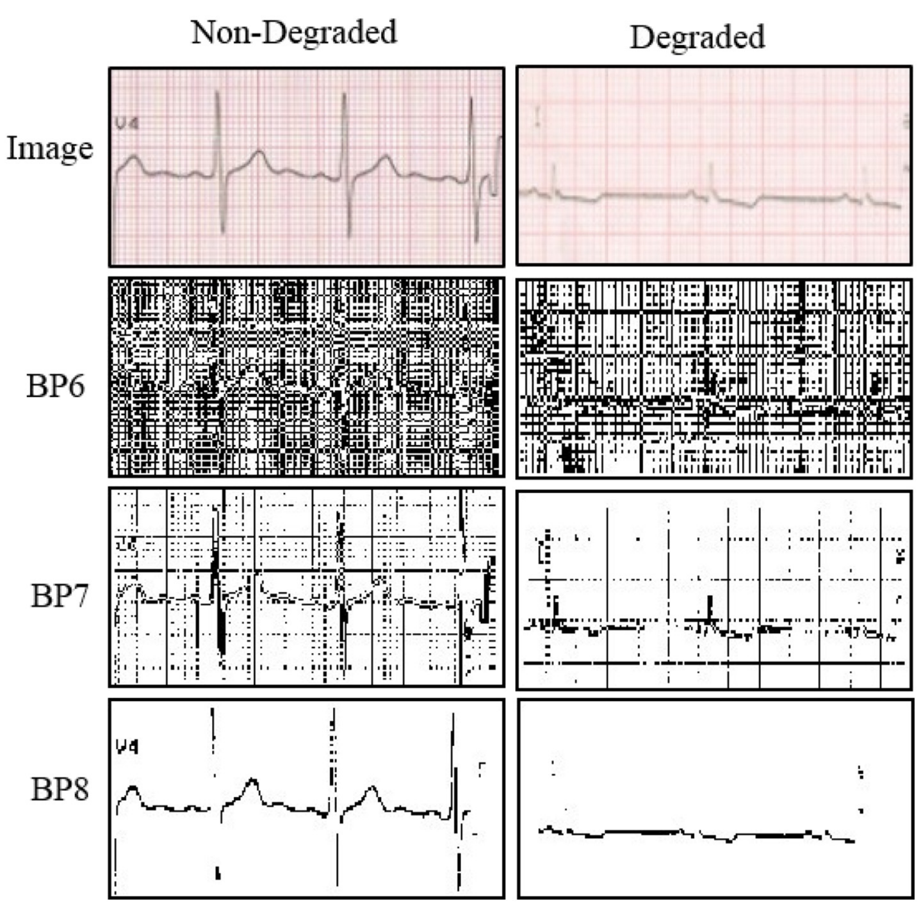

Fig. 1. Last three bit planes out of extracted eight bit planes (BP) from scanned paper ECG image (each row corresponds to a bit plane and column shows different inputs such as degraded and non-degraded ECG's).The required information (i.e. ECG signal trace) was available in 7*th* and 8*th* bit plane. Hence the adaptive selection of bit plane is needed for further processing to decide which bit plane has maximum information about ECG trace.